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THE PHENOMENOLOGY OF THE LIGHTEST PSEUDO NAMBU GOLDSTONE BOSON AT FUTURE COLLIDERS [a]

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The capability of the linear collider to discover and study the lightest neutral pseudo-Nambu-Goldstone boson (P^0) of dynamical symmetry breaking models in the e^+e^- and $\gamma\gamma$ modes is presented. For a number of technicolor $N_{TC}=4$, the discovery of the P^0 at an e^+e^- collider via the reaction $e^+e^- \to \gamma P^0$ should be possible for an integrated luminosity of $L = 100$ fb^{-1} at $\sqrt{s} = 500$ GeV as long as m_{P^0} is not near m_Z. In the $\gamma\gamma$ collider mode the $\gamma\gamma \to P^0 \to b\bar{b}$ signal should be very robust and could be measured with high statistical accuracy for a broad range of m_{P^0} if $N_{TC}=4$.

1 Introduction

Theories of the electroweak interactions based on dynamical symmetry breaking (DSB) avoid the introduction of fundamental scalar fields but generally predict many pseudo-Nambu-Goldstone bosons (PNGB's) due to the breaking of a large initial global symmetry group G. Among the PNGB's the colorless neutral states are the lightest ones. Direct observation of a PNGB would not have been possible at any existing accelerator, however light the PNGB's are, unless the number of technicolors, denoted N_{TC}, is very large. The phenomenological analysis presented here is extracted from ref.[1], where all the details can be found, and is based on a $SU(8)\times SU(8)$ effective low-energy Lagrangian approach. In the broad class of models considered, the lightest neutral PNGB P^0 is of particular interest because it contains only down-type techniquarks (and charged technileptons) and thus will have a mass scale that is most naturally set by the mass of the b-quark. The P^0 total width is typically in the few MeV range and dominant decay modes are $b\bar{b}$, $\tau^+\tau^-$ and gg. Other color-singlet PNGB's will have masses most naturally set by m_t, while color non-singlet PNGB's will generally be even heavier.

Detection of the PNGB's at the Tevatron and LHC colliders, has been extensively considered [2]. However, inclusive gg fusion production of a neutral

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PNGB, followed by its decay to $\gamma\gamma$, was not given detailed consideration until recently [1]. In this paper it was noticed that for a particular class of models the ratio $\Gamma(P^0 \to gg)B(P^0 \to \gamma\gamma)/\Gamma(H \to gg)B(H \to \gamma\gamma)$ with H being the SM Higgs and $N_{TC} = 4$ is of the order 10^2 for $50 \leq m_{P^0/H}(\text{ GeV}) \leq 150$. Therefore, using the results on the Higgs analysis, we can conclude that, for $N_{TC} = 4$, the P^0 can be detected in the $gg \to P^0 \to \gamma\gamma$ mode for at least $30 - 50 < m_{P^0} < 150 - 200$ GeV, or perhaps also at Tevatron RunII with $S/\sqrt{B} \geq 3$ for $m_{P^0} \geq 60$ GeV.

2 e^+e^- mode

The best mode for P^0 production at an e^+e^- collider (with $\sqrt{s} > m_Z$) is $e^+e^- \to \gamma P^0$. Because the $P^0 Z\gamma$ coupling-squared is much smaller than the $P^0\gamma\gamma$ coupling-squared, the dominant diagram is $e^+e^- \to \gamma \to \gamma P^0$. Even when kinematically allowed, rates in the $e^+e^- \to ZP^0$ channel are substantially smaller, as we shall discuss. We will give results for the moderate value of $N_{TC} = 4$. For $\sqrt{s} = 200$ GeV, we find that, after imposing an angular cut of $20^\circ \leq \theta \leq 160^\circ$ on the outgoing photon (a convenient acceptance cut that also avoids the forward/backward cross section singularities but is more than 91% efficient), the $e^+e^- \to \gamma P^0$ cross section is below 1 fb for $N_{TC} = 4$. Given that the maximum integrated luminosity anticipated is of order $L \sim 0.5$ fb^{-1}, we conclude that LEP2 will not allow detection of the P^0 unless N_{TC} is very large.

The cross section for $e^+e^- \to \gamma P^0$ at $\sqrt{s} = 500$ GeV, after imposing the same angular cut, ranges from 0.9 fb down to 0.5 fb as m_{P^0} goes from zero up to $\sim$ 200 GeV. For $L = 50$ fb^{-1}, we have at most 45 events with which to discover and study the P^0. The $e^+e^- \to ZP^0$ cross section is even smaller. Without cuts and without considering any specific Z or P^0 decay modes, it ranges from 0.014 fb down to 0.008 fb over the same mass range. If TESLA is able to achieve $L = 500$ fb^{-1} per year, γP^0 production will have a substantial rate, but the ZP^0 production rate will still not be useful. Since the γP^0 production rate scales as N_{TC}^2, if $N_{TC} = 1$ a $\sqrt{s} = 500$ GeV machine will yield at most 3 (30) events for $L = 50$ fb^{-1} (500 fb^{-1}), making P^0 detection and study extremely difficult. Thus, we will focus our analysis on the $N_{TC} = 4$ case.

In order to assess the γP^0 situation more fully, we must consider backgrounds. The dominant decay modes of the P^0 are typically to $b\overline{b}$, $\tau^+\tau^-$ or gg. For the $b\overline{b}$ and gg modes, the backgrounds relevant to the γP^0 channel are $\gamma b\overline{b}$, $\gamma c\overline{c}$ and $\gamma q\overline{q}$ ($q = u, d, s$) production. The cross sections for these processes obtained after integrating over a 10 GeV bin size in the quark-antiquark mass

are, for $10 \lesssim m_{P^0} \lesssim 80$ GeV and $m_{P^0} \geq 100$ GeV, of the same order of the signal.

Results for $S/\sqrt{B}$, in the various tagged channels, for $N_{TC} = 4$ and assuming $L = 100$ fb^{-1} (and $L = 500$ fb^{-1}) at $\sqrt{s} = 500$ GeV, are plotted in Fig. 1. We have assumed a mass window of $\Delta M_X = 10$ GeV in evaluating the backgrounds in the various channels. Also shown in Fig. 1 is the largest $S/\sqrt{B}$ that can be achieved by considering (at each m_{P^0}) all possible combinations of the gg, $c\bar{c}$, $b\bar{b}$ and $\tau^+\tau^-$ channels. From the figure, we find for $L = 100$ fb^{-1} $S/\sqrt{B} \geq 3$ (our discovery criterion) for $m_{P^0} \leq 75$ GeV and $m_{P^0} \geq 130$ GeV, *i.e.* outside the Z region. A strong signal, $S/\sqrt{B} \sim 4$, is only possible for $m_{P^0} \sim 20 - 60$ GeV. As the figure shows, the signal in any one channel is often too weak for discovery, and it is only the best channel combination that will reveal a signal. For the TESLA $L = 500$ fb^{-1} luminosity, $S/\sqrt{B}$ should be multiplied by ~ 2.2 and discovery prospects will be improved. Tagging and mistagging efficiencies have been included [1].

After discovery, one can determine branching fractions in various channels and couplings. The only channel with reasonable ($\leq 15\%$) statistical error would be $b\bar{b}$, for $L = 500$ fb^{-1}.

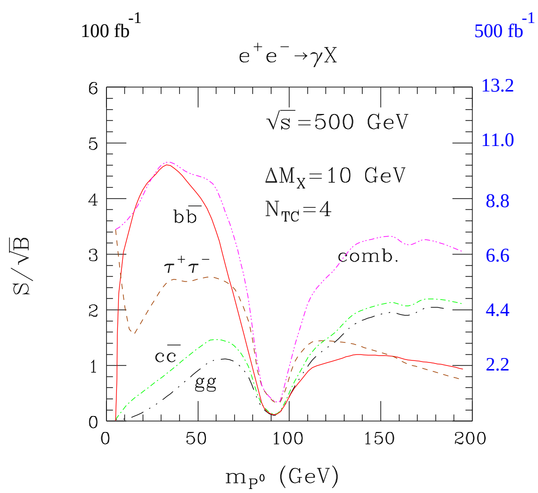

Figure 1: The statistical significances $S/\sqrt{B}$ for a P^0 signal in various 'tagged' channels as a function of m_{P0} at a 500 GeV collider for integrated luminosities of 100 fb^{-1} and 500 fb^{-1}.

3 $\gamma\gamma$ mode

By folding the cross section for the P^0 production at a given energy $E_{\gamma\gamma}$ of a $\gamma\gamma$ collider with the differential luminosity, one gets [3]

$$
\begin{aligned}
N(\gamma\gamma \to P^0 \to F) \quad &= \quad \frac{8\pi\Gamma(P^0 \to \gamma\gamma)B(P^0 \to F)}{m_{P^0}^2 E_{e^+e^-}} \tan^{-1}\frac{\Gamma_{\rm exp}}{\Gamma_{P^0}^{\rm tot}} \\
&\quad \times (1 + \langle\lambda\lambda'\rangle)\, G(y_0) L_{e^+e^-}\,, \qquad (1)
\end{aligned}
$$

where $y_0 = m_{P^0}/E_{e^+e^-}$, λ and λ' are the helicities of the colliding photons, $\Gamma_{\rm exp}$ is the mass interval accepted in the final state F and $L_{e^+e^-}$ is the integrated luminosity for the colliding electron and positron beams. For initial discovery one chooses initial laser polarizations P and P' and e^+e^- beam helicities λ_e and λ_e' for a broad spectrum $2\lambda_e P \sim +1$, $2\lambda_e' P' \sim +1$, $PP' \sim +1$ such that $G \gtrsim 1$ and $\langle\lambda\lambda'\rangle \sim 1$ (which suppresses $\gamma\gamma \to q\overline{q}$ backgrounds) over the large range $0.1 \leq y_0 \leq 0.7$. The P^0 is always sufficiently narrow that $\tan^{-1} \to \pi/2$. In this limit, the rate is proportional to $\Gamma(P^0 \to \gamma\gamma)B(P^0 \to F)$. For the P^0, $\Gamma(P^0 \to \gamma\gamma)$ is large and the total production rate will be substantial.

Since it is well-established [3,4,5] that the SM h can be discovered in this decay mode for $40 \lesssim m_h \lesssim 2m_W$, it is clear that P^0 discovery in the $b\overline{b}$ final state will be possible up to at least 200 GeV, down to $\sim 0.1\sqrt{s} \sim 50$ GeV (at $\sqrt{s} \sim 500$ GeV), below which $G(y)$ starts to get small. Discovery at lower values of m_{P^0} would require lowering the $\sqrt{s}$ of the machine. For the $b\overline{b}$ channel, the statistical significance $S/\sqrt{B}$ is plotted in Fig. 2.

Once the P^0 has been discovered, either in $\gamma\gamma$ collisions or elsewhere, one can configure the $\gamma\gamma$ collision set-up so that the luminosity is peaked at $\sqrt{s}_{\gamma\gamma} \sim m_{P^0}$. A very precise measurement of the P^0 rate in the $b\overline{b}$ final state will then be possible if $N_{TC} = 4$. For example, rescaling the SM Higgs 'single-tag' results of Table 1 of Ref. [5] (which assumes a peaked luminosity distribution with a total of $L = 10$ fb^{-1}) for the 106 GeV $\leq m_{jj} \leq$ 126 GeV mass window to the case of the P^0, we obtain $S \sim 5640$ compared to $B \sim 325$, after angular, topological tagging and jet cuts. This implies a statistical error for measuring $\Gamma(P^0 \to \gamma\gamma)B(P^0 \to b\overline{b})$ of $\lesssim 1.5\%$. Systematic errors will probably dominate. Following the same procedure for $N_{TC} = 1$, we find (at this mass) a statistical error for this measurement of $\lesssim 5\%$. Of course, for lower masses the error will worsen. For $N_{TC} = 4$, we estimate an error for the $b\overline{b}$ rate measurement still below 10% even at a mass as low as $m_{P^0} = 20$ GeV (assuming the $\sqrt{s}$ of the machine is lowered sufficiently to focus on this mass without sacrificing luminosity). For $N_{TC} = 1$, we estimate an error for the $b\overline{b}$ rate measurement of order $15 - 20\%$ for $m_{P^0} \sim 60$ GeV.

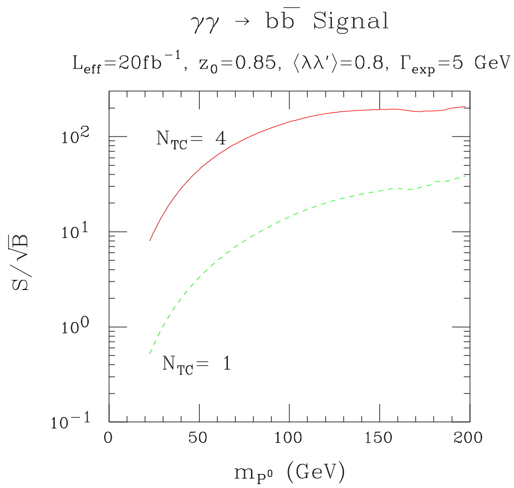

Figure 2: The statistical significance $S/\sqrt{B}$ for $N_{TC}=4$ and $N_{TC}=1$ at a 500 GeV $\gamma\gamma$ collider.

4 Conclusions

We have reviewed the production and study of the lightest pseudo-Nambu Goldstone state P^0 of a typical technicolor model at future colliders, focusing mainly on e^+e^-. For $N_{TC}=4$, discovery of the P^0 in the $gg\to P^0\to\gamma\gamma$ mode at the LHC will be almost certainly be possible unless its mass is either very small ($\lesssim 30$ GeV?) or very large ($\gtrsim 200$ GeV?), where the question marks are related to uncertainties in LHC backgrounds in the inclusive $\gamma\gamma$ channel.

In contrast, an e^+e^- collider, while able to discover the P^0 via $e^+e^-\to\gamma P^0$, so long as m_{P^0} is not close to m_Z and $N_{TC}\geq 3$, is unlikely (unless the TESLA 500 fb^{-1} per year option is built or N_{TC} is very large) to be able to determine the rates for individual γF final states ($F=b\overline{b},\tau^+\tau^-,gg$ being the dominant P^0 decay modes) with sufficient accuracy as to yield more than very rough indications regarding the important parameters of the technicolor model.

The $\gamma\gamma$ option at an e^+e^- collider is actually a more robust means for discovering the P^0 than direct operation in the e^+e^- collision mode. For $N_{TC}=4$, $\gamma\gamma\to P^0\to b\overline{b}$ should yield an easily detectable P^0 signal for $0.1\lesssim\frac{m_{P0}}{\sqrt{s}}\lesssim 0.7$. Once m_{P^0} is known, the $\gamma\gamma$ collision set-up can be re-configured to yield a luminosity distribution that is strongly peaked at $\sqrt{s}_{\gamma\gamma}\sim m_{P^0}$ and, for much of the mass range of $m_{P^0}\lesssim 200$ GeV, a measurement of

$\Gamma(P^0 \to \gamma\gamma)B(P^0 \to b\bar{b})$ can be made with statistical accuracy in the $\lesssim 2\%$ range.

A $\mu^+\mu^-$ collider would be crucial for detecting a light P^0 ($m_{P^0} \lesssim 30$ GeV) and would play a very special role with regard to determining key properties of the P^0 [1]. In particular, the P^0, being, in the class of models we have considered, comprised of $D\overline{D}$ and $E\overline{E}$ techniquarks, will naturally have couplings to the down-type quarks and charged leptons of the SM. Thus, s-channel production ($\mu^+\mu^- \to P^0$) is predicted to have a substantial rate for $\sqrt{s} \sim m_{P^0}$. Because the P^0 has a very narrow width, in order to maximize this rate it is important that one operates the $\mu^+\mu^-$ collider so as to have extremely small beam energy spread, $R = 0.003\%$. The complete analysis of how the precision $\mu^+\mu^-$ measurements of various channel rates together with LHC and e^+e^- measurement can determine (up to a discrete set of ambiguities) the parameters of the effective low-energy Yukawa Lagrangian that determine $T_3 = -1/2$ fermion masses and their couplings to the P^0 can be found in [1].

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